AN E-BEAM CONTROLLED DIFFUSE DISCHARGE SWITCH

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Abstract: The control efficiency and the response time of electron-beam controlled diffuse discharges is to a large extent determined by atomic and molecular properties of the switch gas composition. An e-beam tetrode was used to study switch gas properties for submicrosecond opening switches. Electrical measurements were performed with various switch gas mixtures containing small amounts of electronegative gases. Of particular interest were mixtures of N_2O:N_2 and C_2F_6:Ar. In both gas mixtures the resistivity increases with electric field strength. This effect is particularly strong in a mixture of 2% C_2F_6 in 1 atm Ar, where an increase of 25 was obtained in a reduced field strength range of 1 Td < E/N < 20 Td. The current decay times or opening times with this mixture were below 100 ns. Optical time resolved investigations of discharges in C_2F_6:Ar showed the occurence of striations which were perpendicular to the discharge axis. These luminous layers in the discharge can be explained as domain formations similar to those observed in direct semiconductors as e.g. the Gunn-effect in GaAs.

Introduction

Electron-beam controlled diffuse discharges can be used as fast, repetetively operated closing and opening switches. The concept is as follows: The gas between the electrodes conducts when the ionizing e-beam is injected and the switch closes. The switch voltage remains below the self-breakdown voltage, so that avalanche ionization is negligible. Thus the discharge is completely sustained by the e-beam. When the e-beam is turned off, electron attachment and recombination processes in the gas cause the conductivity to decrease and the switch opens.

In order to achieve opening times of less than a microsecond at initial electron densities of $n_e < 10^{14}$ cm^{-3}, the dominant loss must be attachment. That means that the switch gas mixture must contain an electronegative gas which, however, lowers the efficiency of the switch. It causes a reduction of the current gain (switch current/e-beam current) proportional to the opening time. If the switch is part of an inductive energy circuit, both high current gain and fast opening can be obtained by choosing gas mixtures which satisfies the conditions [1,2,3]:
a) For low values of the reduced field strength E/N (conduction phase) the gas mixture should have a high drift velocity v_d and low attachment rate k_a.
b) For high E/N values (opening phase) the gas mixture should have lower drift velocities and high attachment rate coefficients.

Experimental Setup

For the investigation of e-beam controlled conductivity in a high pressure gas mixture with properties as discussed above, a discharge system was constructed with an e-beam tetrode as control element [4]. A schematic cross-section of the tetrode and the discharge chamber is shown in Fig. 1. The e-beam cathode is located in the Pyrex cylinder between the two plates of a stripline and consists of an electrically heated array of thoriated tungsten filaments. At a filament temperature of 2100 K, the e-beam current density is about 4 A/cm^2 over the 100 cm^2 cross-sectional area of the beam. The temporal structure of the e-beam is controlled by means of a control grid which allows the generation of a pulse train with pulse duration and pulse separation in the 100 ns time range. For some investigations the e-beam was operated as a cold cathode system, which provided e-beam current pulses of 15 A with a pulse duration of~400 ns.

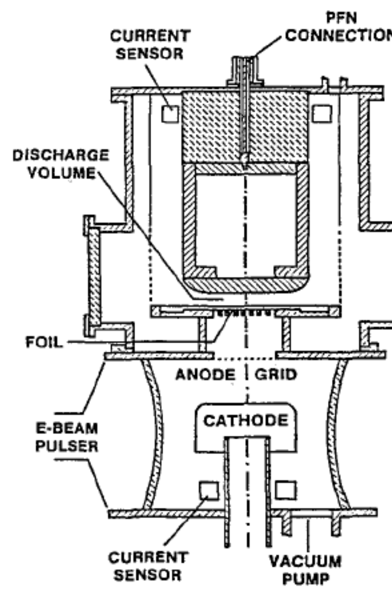

Fig. 1. Cross Section of E-Beam Tetrode and Switch Chamber.

The e-beam voltage is applied to the anode by a two-stage Marx generator, which delivers a maximum voltage of 250 kV with a 5 ns risetime and with an exponential decay time constant of about 2.5 microseconds into a 300 Ohm load. After passing through a 25 μm titanium foil and a 12.5 μm aluminum foil, which serves as an electrode in the diffuse discharge switch, the e-beam generates a diffuse plasma between the electrodes in the stainless steel discharge chamber. The current through the plasma is provided by a 2 Ohm pulse forming network.

Measurements of the e-beam current and the switch current were performed by means of transmission line current transformers [5]. Voltages were measured with fast resistive voltage dividers. In order to get information on the spatial structure of the discharge an image converter camera was built [6] using an ITT image converter diode type F4109. The camera has a high sensitivity of 225 μA/ℓm and a high spatial resolution of 45 ℓp/mm. The shutter time was about 10 ns.

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Experimental Results

Diffuse discharge experiments were performed in N_2O, SO_2, and CO_2 with N_2 as buffer gas, and C_2F_6 in Ar. The source term, the number of electrons produced per cm^3 second, was in the range of 10^{20} $cm^{-3}s^{-1}$ to 10^{21} $cm^{-3}s^{-1}$. The voltage applied at the PFN was varied between 100 Volts and 20 kV. The switch electrode gap was kept constant at 3.5 cm. Most of the measurements were performed with the $N_2O:N_2$ gas mixture. This gas combination was for one expected to satisfy the conditions for switch gases nicely (see introduction) and secondly it allowed modeling of the diffuse discharge [7], since a complete set of cross sections is available for N_2 [8] and the plasma chemistry in a mixture of N_2 and N_2O appeared to be relatively simple.

Figure 2 shows the influence of the attacher c concentration (N_2O) on the opening time. For high N_2O concentrations (3 %) the switch current replicates the e-beam current, except for the tail. The tail is caused by the current carried by positive and negative ions. The current gain is about 2 for this attacher concentration. For concentrations of .7 % the fall time (1/e -time) increases to approximately 100 ns. For .1 % it is in the order of 500 ns. The gain increases to values of 9 and 12, respectively.

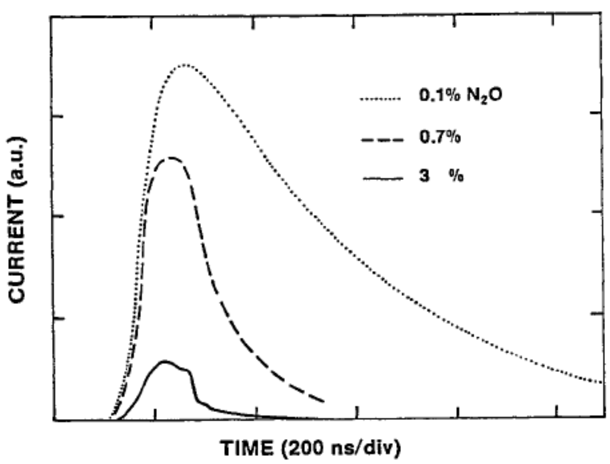

Fig. 2. Normalized Switch Current for Different Attacher Concentrations. Demonstrating the Strong Effect of the Attacher on the Current Decay (Opening Time).

Figure 3 shows the experimentally obtained current density (j) values (dots) versus reduced field strength E/N for the e-beam sustained discharge under steady state conditions in 1 atm N_2 with .7% N_2O. The curve represents calculated values [9] which were critically depending on available attachment rate coefficients or cross sections [10,11,12]. The good coincidence between model and experiment was obtained with attachment cross sections measured by Chantry [12].

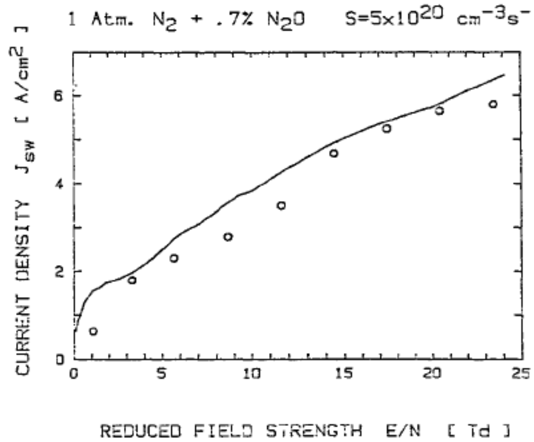

Fig. 3. Current Density j versus Reduced Field Strength E/N for a Discharge in $N_2O:N_2$ (Calculated Curve and Experimental Data Points).

In Fig. 4 the experimental and theoretical data are plotted in a resistivity ρ_0 versus E/N diagram. The desired opening switch effect, an increase in resistivity with increasing electric field, is obtained with the $N_2O:N_2$ gas mixture. However, the increase is moderate: about 2.5 over a field strength

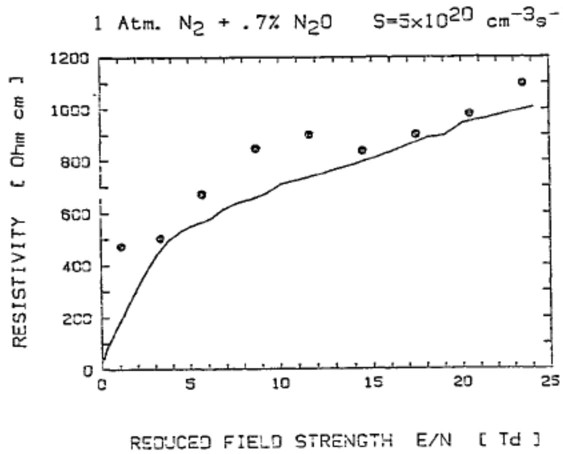

Fig. 4. Discharge Resistivity ρ_0 versus E/N for a Discharge in $N_2O:N_2$ (Calculated Curve and Experimental Data Points.)

range of 25 Td. The strong deviation of the lowest experimental value from the computed curve is probably due to the fact that the cathode fall was not included in our model. Gas combinations of SO_2 and CO_2 with N_2 as buffer gas showed even smaller changes in resistivity at comparable opening times.

A group of very promising gases, what the opening switch conditions concerns (see introduction), were proposed by Christophourou et. al., [3]. The total attachment rate constant k_a is plotted versus mean electron energy ϵ in Fig.5. Measurements performed with the gas mixture of 2 % C_2F_6 in 1 atm Ar as buffer gas gave as a result a very strong increase in resistivity with field strength (Fig.6). Decay (opening) times for this mixture were below 100 ns. The mixture seems to be relatively stable.

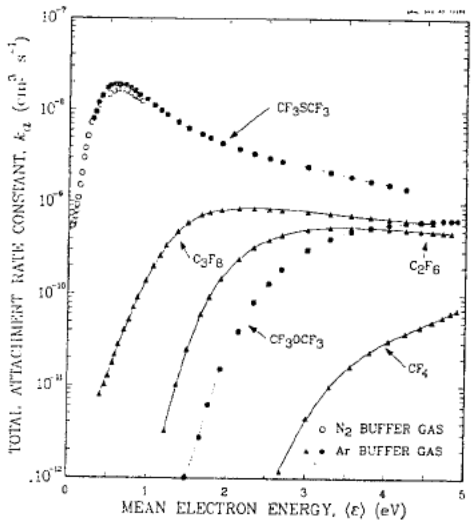

Fig. 5. Gases with Strong Increase of Attachment Rate Coefficient with Electron Energy [13].

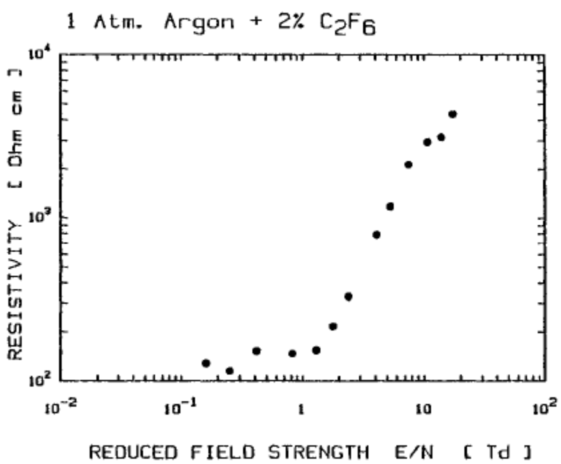

Fig. 6. Discharge Resistivity ρ_0 versus E/N for a Discharge in C_2F_6:Ar.

Reproducable results at an e-beam voltage of 150 kV were obtained for 150 shots without changing the gas.

The current density (j) versus reduced field strength (E/N) curve for this gas mixture is shown in Fig. 7. It contains a region with very pronounce negative differential conductivity (NDC). The effect which causes NDC in externally sustained diffuse discharges containing attachers is due to the increased generation of negative ions, that means

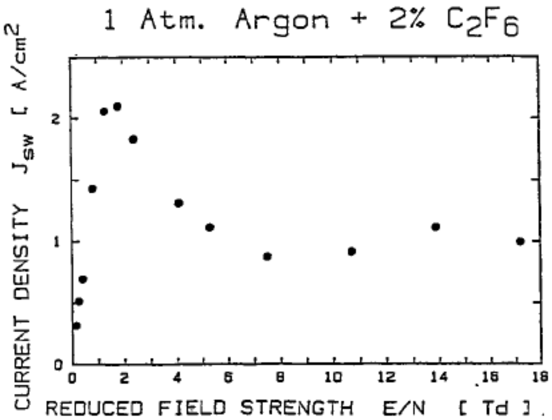

Fig. 7. Current Density j versus Reduced Field Strength E/N for a Discharge in C_2F_6:Ar.

negative charges with increased mass, above a certain electron energy. A similar effect is known and widely applied for high frequency generation and amplification in semiconductors, as e.g. GaAs [14]. The negative differential conductivity in semiconductors is caused similarly as in diffuse discharges by an increase in the effective mass of the electrons at higher electron energies [15]. The presence of NDC in semiconductors causes homogeneous material to become electrically heterogeneous thus causing high field dipole domains to form and propagate through the semiconductor (Gunn-effect).

The same effect, formation of high field domains, can be expected in externally sustained discharges with gas mixtures such as C_2F_6 in Ar. In order to prove this, the discharge was optically recorded by means of an image converter camera with a shutter time of 10 ns. Figure 8a shows side-on photographs of the discharge at different times after e-beam turn-on, Fig. 8b the corresponding photometer curves along the discharge axis. The discharge was biased so that the point of operation was in the NDC-region of the j-E/N characteristic (Fig. 7). The pictures show clearly the development of a highly luminous layer in the cathode region of the discharge. Its profile is dependent on the bias voltage; for bias points on the left hand side of the current density maximum the discharge appears homogeneous.

We consider the region of high luminosity as a high field domain, a region of enhanced energy dissipation, similar to the ones observed in semiconductors. The reduction in the width of these structures can be explained by the more than linear increase in the attachment rate coefficient in the NDC-region. A propagation of the high field domains in anode direction could not be observed. The reasons are the shot-to-shot variations in the structure which did not allow exact timing and the expected relatively slow motion of the layer ($v = 10^5 - 10^6$ cm/s).

The development of high field domains has probably little effect on the opening switch behavior of an e-beam controlled discharge; however, it may lead to more applications for these type of discharges. The analogy to the Gunn effect in GaAs points to the initiation of e-beam sustained discharges as high power, high frequency oscillators and amplifiers. Preliminary calculations indicate power levels of > 100 kW at frequencies < 1 GHz.

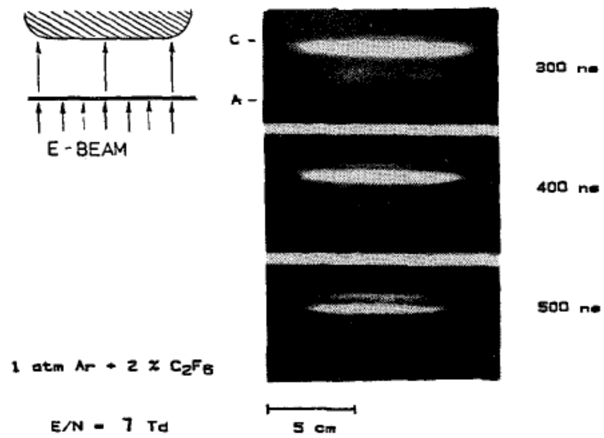

Fig. 8a Temporal Development of Striations in the E/N Range with Negative Differential Conductivity.

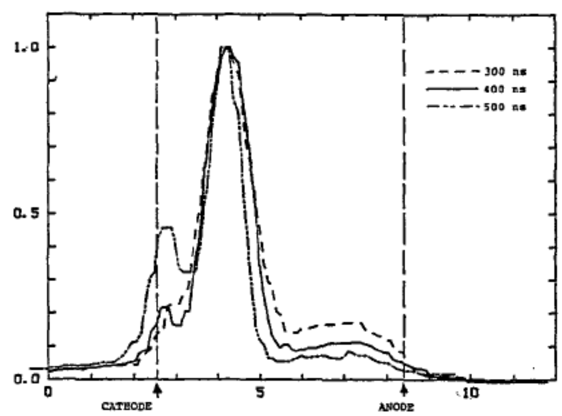

Fig. 8b. Photometer Curves of the Discharge Along the Discharge Axis.

Summary

Different gas mixtures were tested for their use as switch gases in diffuse discharge opening switches. Best results were obtained with a mixture of C_2F_6 and Ar as buffer gas. For a mixture of 2% C_2F_6 in 1 atm Ar opening times of less than 100 ns were measured. The increase in resistivity was almost two orders of magnitude in a field strength range up to 25 Td. The current gain for this gas combination at a pressure of 6 atm and e-beam energies of 165 keV would be about 100. The current density-reduced field strength characteristic of the e-beam controlled discharge in C_2F_6:Ar has a distinct region with negative differential conductivity. This effect causes the formation of luminous striations in the discharge. The analogy between this type of discharge and semiconductors, which exhibit NDC, might lead to applications for externally sustained diffuse discharges as high power oscillators and amplifiers.

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